Operational analysis of 5 PVT heat pump systems based on field measurement data

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Abstract

On December 1, 2019, the integraTE joint project of the three research institutes Fraunhofer ISE, the Institute for Building Energetics, Thermotechnology and Energy Storage of the University of Stuttgart and the Institute for Solar Energy Research Hameln started. The aim of the project is to achieve an increased market penetration with technically as well as economically attractive systems for thermal and electrical energy supply by means of PVT collectors and heat pumps in the building sector. Within the framework of the project, demonstration plants in single family buildings are examined metrologically.

This conference paper presents the results of the metrological investigation of 5 demonstration plants over the period from June 2021 to July 2022.

Keywords: WISC PVT-collector, heat pump, ground source, single family building, monitoring

1. Introduction

T Since the start of the project a comprehensive measurement recording has been started for 5 demonstration systems in single family buildings. The plants are very heterogeneous in their characteristics. While all systems work in single-family homes, different collector technologies are used. Three buildings were renovated (RE), two are new buildings (NB) With two systems, the PVT collector is the only source of heat for heat pump. In the other three plants, a geothermal source comes along additionally. The following Tab 1 lists the characteristics of the examined plants.

Tab 1: characteristics of the demonstration plants,

plant nr.	type	heated area in m²	final energy demand in kWh/m²*a	PVT type	collector-surface in m²	th. power PVT in kW	el. Power PVT/PV in kWh_p	battery-storage kWh	additional heat source	heating capacity HP (B0/W35) in kW	COP (B0/W35)	second heat producer
1	RE	411	80	PVT (WISC)	88	46.3	23.7	20.0	-	13	5	condens-ing gas
2	RE	246	100	Integrated in roof insulation	55	15.6	4.5	no	borehole 390 m	20	4.4	electric
3	RE	340	100	PVT (WISC)	30.6	19.2	14.4	no	borehole 170 m	16	4.6	electric
4	NB	190	40	PVT (WISC) with air HEX	15.8	10.7	12.3	7	-	4.7	4.3	electric
5	NB	310	50	PVT (WISC)	56.1	38.4	7.2	11.4	earth heat collector 25 m	12	4.8	electric

The plants are equipped with heat meters and electricity meters to measure all relevant energy flows as well as

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temperatures around heat pump, PVT collector and ground source. Ambient conditions such as temperature, humidity and global irradiation are measured additionally.

The systems are first evaluated regarding the efficiency of the heat pump heating system. For this purpose, the system performance factor SPF defined in the following is used.

2. Key performance indicators

In the following the balance boundary and the system seasonal performance factor is being defined. Subsequently the KPIs of the five plants are discussed.

Definition of the balance boundary and the system seasonal performance factor

The plants are evaluated on the basis of the system performance factor SPF_bST (seasonal performance factor before storage).

$$\text{SPF\_bST} = \frac{\int (\dot{Q}_{HP} + \dot{Q}_{backup} + \dot{Q}_{PVT,parallel})\, dt}{\int (\dot{E}_{comp} + \dot{E}_{Heizstab} + \dot{E}_{Pumpen,prim})\, dt} \qquad \text{eq. 1}$$

with:

$\dot{Q}_{HP}$:	amount of heat delivered by the HP for space heating and domestic hot water [kWh].
$\dot{Q}_{backup}$:	amount of heat emitted by the heating rod[kWh]
$\dot{Q}_{PVT,parallel}$	amount of heat supplied to and removed from the storage tank by the PVT collector [kWh].
$\dot{E}_{comp}$	electrical energy consumed by the HP (compressor) [kWh].
$\dot{E}_{backup}$:	electrical energy consumed by the heating rod [kWh].
$\dot{E}_{Pumpen,prim}$	electrical energy consumed by heat source pump(s) [kWh].

System seasonal performance factor and temperatures of heat source and heat sink

The following Figure 1 shows the seasonal performance factor of the five examined plants sorted in descending order.

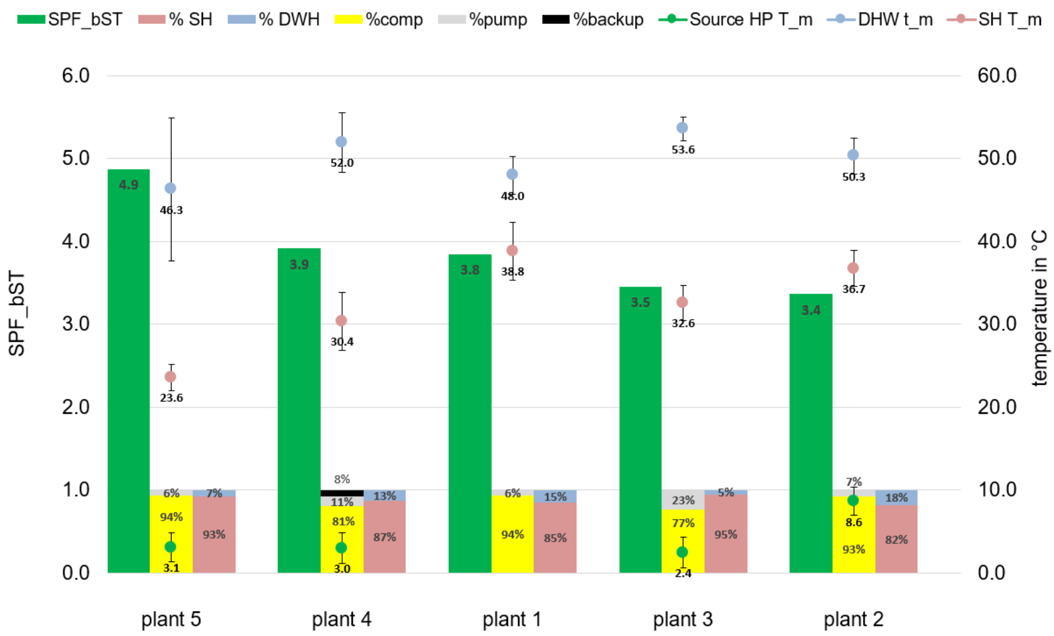

Figure 1: SPF_bST from June 2021 to July 2022

The SPF_bST is indicated as a green column. It reaches from 4.9 at plant 5 to 3.4 at plant 5 for the period under consideration. Next to the green column there is a stacked column. This column shows the share of the electrical energy demand of the compressor, the primary pump(s), and the backup heater in relation to the total electric energy consumption of the heat pump. The energy demand of the controller and the secondary pumps are not considered in this investigation.

At plant 5 the share of the compressor is at 94 %, while the brine pump consumes 6 % of the electrical energy. At plant 4 the compressors energy demand is at 81 % and the brine pump at 11 %. Plant 4 is the only plant where the electrical backup heater was in operation. The share of the electrical energy demand is at 8 % during the considered period.

At plant 1 and plant 5 the distribution of 94 % (93 %) and 6 % (7 %) corresponds to the usual values for those plants. At plant 3 there is a high share of the brine pump with 23 %. At this plant in summertime the PVT collector is used to recharge the borehole. For this reason, there is a high energy demand for the brine pump without the compressor being in operation.

The next stacked column shows the share of thermal energy provided by the heat pump for domestic hot water in blue and the share of energy provided for space heating in red. At plant 5 and plant 3 the share of domestic hot water is with 7 % (5 %) very low for a single-family house. At plant 4, plant 1 and plant 5 the share of domestic hot water ranges between 13 % and 18 %.

Figure 1 furthermore shows the energetically weighted temperatures of the heat source, domestic hot water production and space heating. The graph shows the middle temperature of the respective circuit. It is calculated by the arithmetic mean temperature between supply and return line. At plant 5, plant 4 and plant 3 the middle temperature of the heat source circuit of the heat pump is at 3.1 °C, 3.0 °C and 2.4 °C with a spread of 3 K. At plant 5 the temperature is at 8.6 °C with a spread of 4.4 K. Due to a failure on the heat meter the temperatures at plant 1 could not be measured.

The middle temperature of the domestic hot water production of the heat pump ranges between 46.3 °C with high spread of 17 K and 53.6 °C with a spread of 2.8 K.

The middle temperature of the HP while in space heating mode ranges from 23.6 °C with a spread of 3.2 K at plant 5 and 38.8 °C with a spread of 7 K at plant 1.

The SPF_bSt of the plants is strongly influenced by the temperatures of the heat sink and heat source. Plant 5 has a temperature of the heat source of 3.1 K. The middle temperature of the space heating is at very low 23.6 °C. Furthermore, most of the heat (93 %) has been provided in the space heating mode. Plant 1 runs on a high temperature in the heating mode but has still a SPF_bST of 3.8. At this plant a large amount of heat in the heating mode is produced in summertime for heating the indoor swimming pool which is in the building. Thus, it is to be expected that the heat source temperature was very high at this time.

The SPF of plant 3 is negatively influenced by the high energy demand of the brine pump in summertime. On the other hand, recharging the borehole in summertime results in a better performance of the PV in summertime and a higher temperature of the borehole and consequently of the heat pumps heat source in wintertime.

Heat source PVT and borehole

The following Figure 2 shows once more the SPF_bST as a green column. The next stacked column shows the distribution of the heat pumps source energy. This energy is provided by either the PVT collector indicated in orange or by the borehole which is indicated in brown.

The middle temperature of PVT circuit is indicated in orange. The middle temperature of the borehole is indicated in brown, and the middle temperature of the heat pumps source circuit is indicated as a green dot.

At plant 5 60 % of the energy which is provided as a heat source for the heat pump is delivered by the PVT collectors at a middle temperature of 5.4 °C with a spread of 4.8 K. 40 % of the source energy is provided by the ground collector at a middle temperature of 1.7 °C with a spread of 3.2 K. This results in an average middle Temperature of the heat source of 3.1 °C for this plant.

At plant 4 the PVT collector is the only heat source for the heat pump. The middle temperature is at 3.0 °C with a spread of 3.6 K.

Due to a failure on the heat meter the temperatures at plant 1 could not be measured.

At plant 3, 43 % of the heat pumps source energy is directly provided by the PVT collector at a temperature of 4.4 °C. The borehole provides 57 % of the energy. The middle temperature of the borehole is 0.9 °C with a spread of 1.8 °C. At this plant the PVT collectors are used to recharge the borehole in summertime. When this energy is considered, 71 % of the heat pumps source energy has been delivered by the PVT collector. On a yearly basis the PVT collector was delivering a middle temperature of 13.9 °C with a spread of 5.6 K.

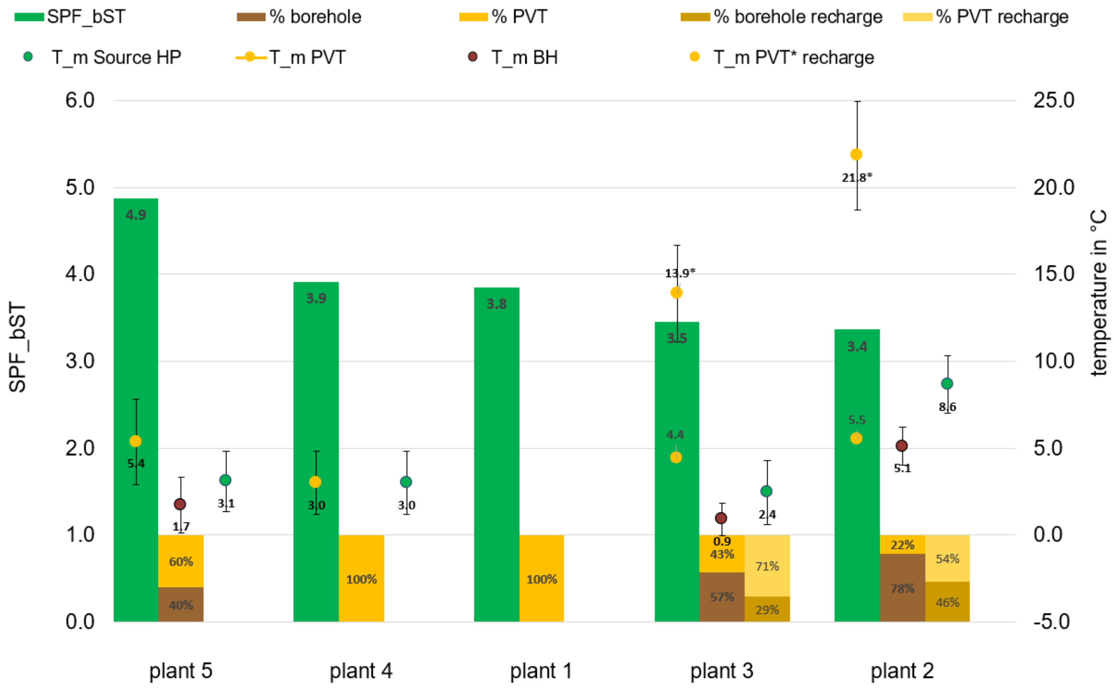

Figure 2: temperatures and energy share of PVT and ground source

At plant 2 22 % of the heat pumps source energy is directly provided by the PVT collector at a temperature of 4.4 °C. The borehole provides 57 % of the energy. The middle temperature of the borehole is 0.9 °C with a spread of 1.8 °C. At this plant the PVT collectors are used to recharge the borehole in summertime. When this energy is considered 54 % of the heat pumps source energy has been delivered by the PVT collector. On a yearly basis the PVT collector was delivering a middle temperature of 21.9 °C with a spread of 6.2 K.

Thermal Energy and temperatures provided by the PVT collector

In the following the thermal energy delivered by the collector is shown exemplarily for plant 4 and plant 3 on a monthly basis. Plant 4 uses WISC collectors with fins to optimize the heat exchange with the ambient air. This plant has no additional heat source for the heat pump. Plant 3 uses standard WISC PVT collectors in combination with a borehole of 170 m depth.

The following Figure 3 shows the amount of energy which is provided by the PVT for every month indicated as an orange column. The energy provided by the PVT collector reaches from 121 kWh in July to 1441 kWh in January. Since the PVT collector is the only heat source for the heat pump, the energy provided to the heat pump shows a direct dependence to the heating demand for domestic hot water and space heating.

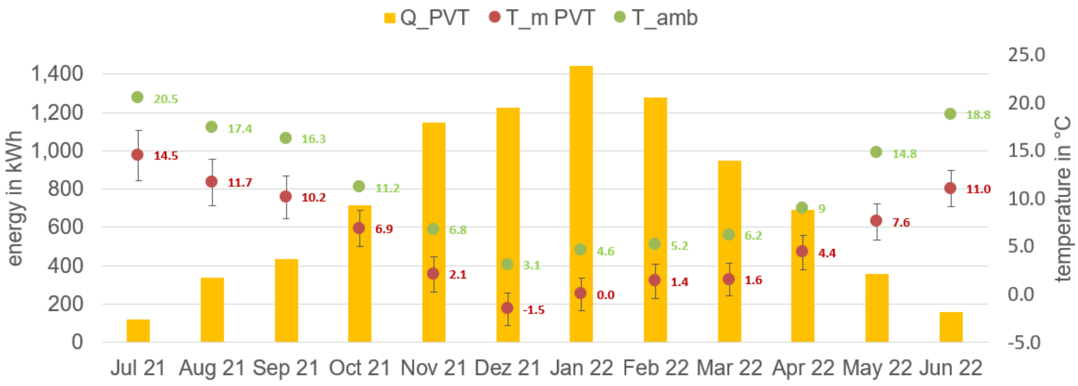

Figure 3; monthly energy and temperatures plant 4

The middle temperature of the PVT circuit is shown as a red dot. The middle temperature reaches from 14.5 °C with a spread of 5.2 K in July to – 1.5 °C with a spread of 3.4 K in December. The average monthly ambient temperature is shown as a green dot and reaches from 20.5 °C in July to 3.1 °C in January. The spread between middle temperature of the PVT circuit and average ambient temperature is at 6 K in July 21. Towards wintertime the spread decreases to its minimum value of 3.8 K in February. Towards summertime it increases again to 7.8 K. In summertime the spread between ambient temperature and middle temperature of the PVT collector is higher. This is caused by the ambient temperature and the solar irradiation at time of the day when the heat pump is in operation.

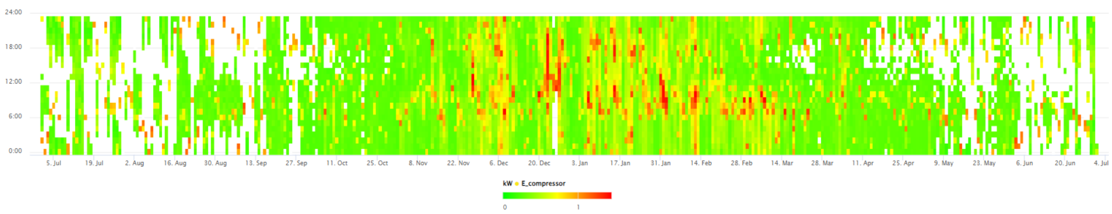

Figure 4: power consumtion of the compressor, plant 4

Figure 4 shows the power consumption of the heat pumps compressor during the year on a minutely basis.
In summertime the heat pump is mostly in operation in the morning. At this time the ambient temperature and the solar irradiation is lower than at noon or afternoon. In wintertime the heat pump runs almost all day long. Additionally the phases with the highest energy demand are later during the day. As a result, the collector benefits more from solar radiation and from higher temperatures during the day in wintertime.

The following Figure 5 shows the amount of energy which is provided by the PVT for every month indicated for plant 3. The energy provided by the PVT collector reaches from 2722 kWh in July to 143 kWh in January. The PVT collector is used in summertime to recharge the borehole, which leads to the monthly energy distribution shown in the plot below.

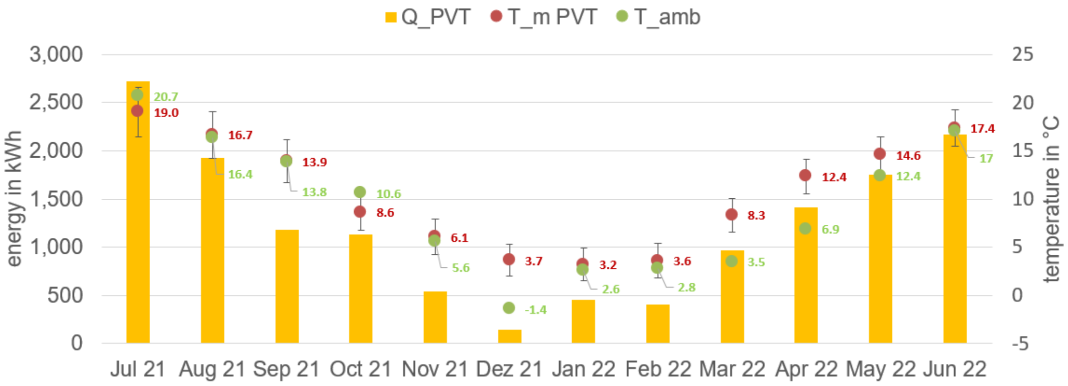

Figure 5: monthly energy and temperatures Plant 3

The middle temperature of the PVT reaches from 19.0 °C with a spread of 7.2 K in July to 3.7 °C with a spread of 1.4 K. The average monthly ambient temperature is shown as a green dot and reaches from 20.7 °C in July to -1.4 °C in January. The spread between middle temperature of the PVT circuit and average ambient temperature does not follow a trend.

The following Figure 6 shows the thermal power provided by the PVT circuit during the year on a minutely basis.

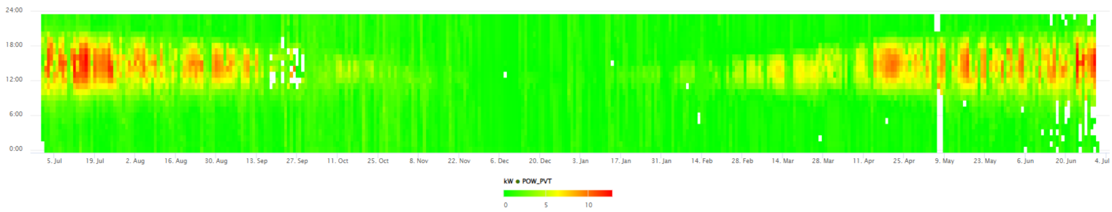

Figure 6: thermal power PVT circuit, plant 3

The PVT circuit was in operation at almost every minute of the year. In summer the thermal power reaches its maximum at 12.7 kW in June. In the winter months the maximum power is at 1.5 kW at daytime an 0.1 kW in the night.

3. Electrical energy demand and production of the plants

The following Figure 7 shows the amount of electrical energy which has been provided by the PV indicated as an orange column. This includes the PVT collectors as well as the additional PV collectors some plants have besides the PVT collectors. The energy consumption of the heat pumps compressor is given in yellow, brine pump(s) in grey and electrical backup heater in black. The green column shows the amount of energy which has been used in the heat pump system for compressor, brine pump(s) and backup heater and which was provided by the PV and the battery. This energy has been calculated on a minutely basis. Furthermore, in addition, the assumption is made that the electricity from PV and battery is provided exclusively to the heating system and is not consumed in the household.

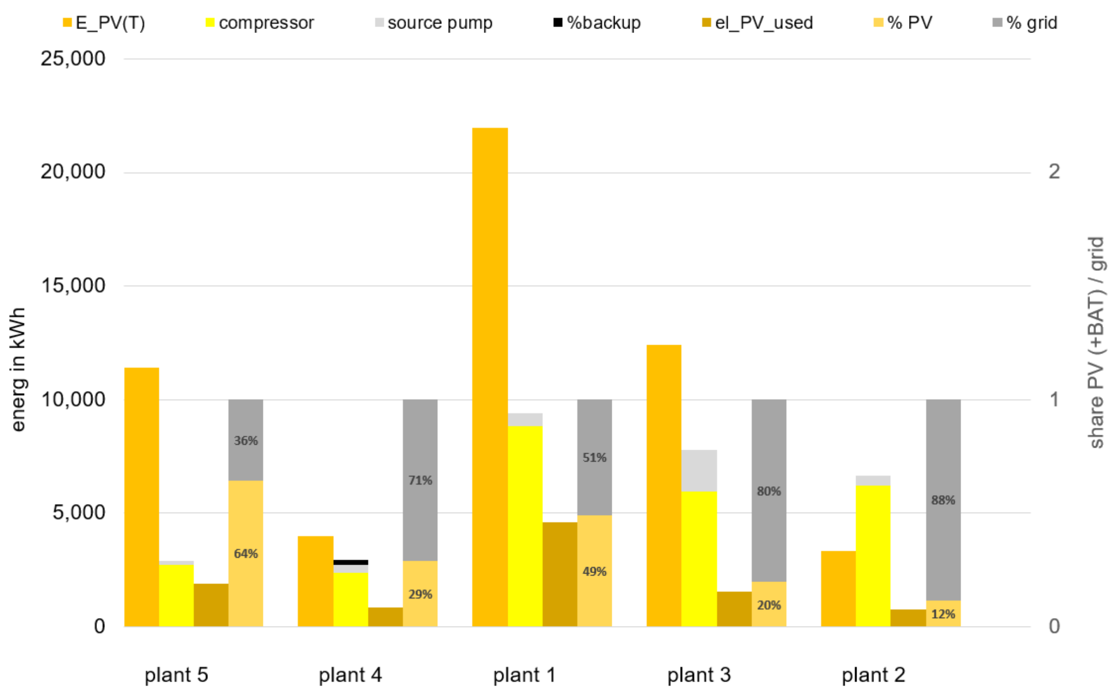

Figure 7: electrical energy PV(T) and heat pump

At plant 5 the PV provides 11400 kWh. The heat pump consumes 2913 kWh. 1876 kWh of the energy provided by the PV has been used in the heating system. That means that 64 % of the heat pumps energy demand has been covered by the PV and battery system. 36 % of the electrical energy was provided by the grid.

At plant 4 the PV provides 3981 kWh. The heat pump consumes 2944 kWh. 1876 kWh of the energy provided by the PV has been used in the heating system. That means that 29 % of the heat pumps energy demand has been covered by the PV and battery system. 71 % of the electrical energy was provided by the grid.

At plant 1 the PV provides 21980 kWh. The heat pump consumes 9401 kWh. 4623 kWh of the energy provided by the PV has been used in the heating system. That means that 51 % of the heat pumps energy demand has been covered by the PV and battery system. 49 % of the electrical energy was provided by the grid.

At plant 3 the PV provides 12408 kWh. The heat pump consumes 7789 kWh. 1533 kWh of the energy provided by the PV has been used in the heating system. That means that 80 % of the heat pumps energy demand has been covered by the PV and battery system. 20 % of the electrical energy was provided by the grid.

At plant 2 the PV provides 3323 kWh. The heat pump consumes 6666 kWh. 777 kWh of the energy provided by the PV has been used in the heating system. That means that 88 % of the heat pumps energy demand has been covered by the PV and battery system. 12 % of the electrical energy was provided by the grid.

In the following the coverage of the heat pumps energy demand by the PV and and the pv + the battery storage has been investigated on a monthly base. The following Figure 8 shows these values for plant 1. This plant is equipped with a battery with a capacity of 20 kWh.

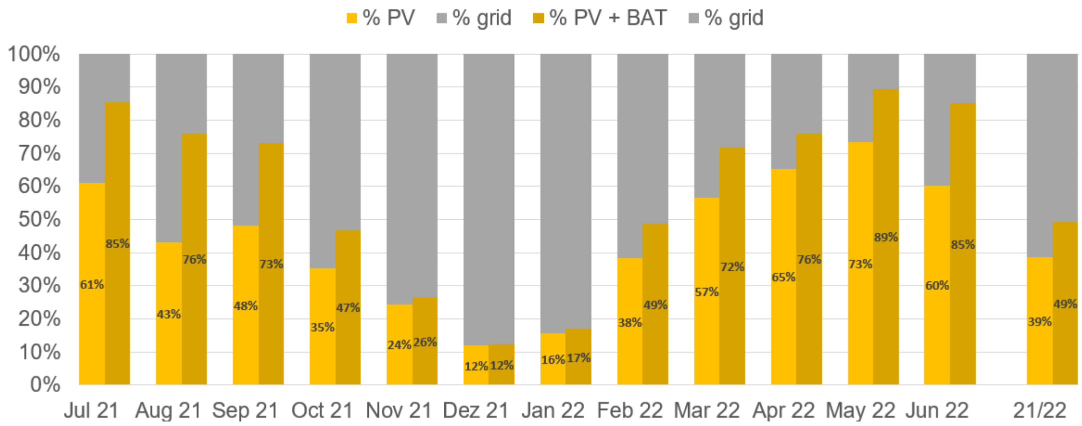

Figure 8: monthly coverage pv (+ bat) electricity, plant 1

In the summer months the heat pumps electricity demand can be covered up to 73 % by the PV. With the help of the battery this value can be raised to 89 %. In the winter months when the electricity demand of the heat pump system is high and the solar irradiation low, the coverage decreases to 12 %. During this time the self-sufficiency level of the system cannot be increased by the battery. During the entire period under consideration from July 21 to June 22, the PV coverage is 39 %. With the help of the battery, it can be raised up to 49 %. It has to be stated that this plant has a high thermal energy demand in summertime which is caused by an indoor swimming pool. This raises the PV coverage in the summer months in comparison to a normal single-family house.

The following Figure 9 shows the coverage of the heat pumps energy demand by the PV and and the pv + the battery storage at plant 4. This plant is equipped with a battery with a capacity of 7 kWh. It was not possible to measure the PV and the battery separately. For that reason, the following plot considers the electrical energy which has been delivered by the PV and the battery.

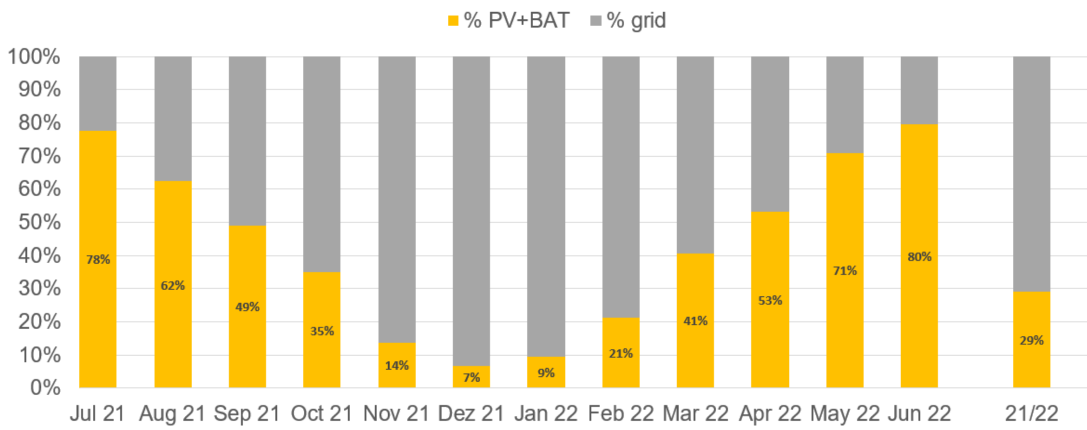

Figure 9: monthly coverage pv (+ bat) electricity, plant 4

In the summer months the heat pumps electricity demand can be covered up to 80 % by the PV and the battery. In the winter months when the electricity demand of the heat pump system is high and the solar irradiation low, the coverage decreases to 7 %. During the entire period under consideration from July 21 to June 22, the PV+BAT coverage is at 29 %.

4. Summary

PVT collectors are suitable as a heat source for building heating systems with heat pumps. The SPF of the five plants range between 3.4 and 4.9. As usual for heat pumps the SPF depends mostly on the heat sink temperatures. systems with a low heating circuit temperature and a low quantity of produced drinking hot water yield the highest SPF. When normal WISC collectors are used, the plant should either be equipped with an additional ground source. In those cases, the PVT collectors can be used both to recharge the ground source during summertime and to increase the temperature of the heat source for the heat pump. As an alternative to that a condensing gas boiler can support the system in the winter months. WISC PVT collectors with an optimized ambient air heat exchanger can work as a single heat source for the heat pump system. The plant which has been the system convinces with a reasonable use of the heating rod in wintertime.

During the period under consideration of one year, the plants can cover between 12 % and 64 % of the electrical energy demand for the heating system by pv electricity. However, values above 20 % could only be achieved with the help of a battery.

The study also showed that there is potential for optimization in all plants. For example, all plants are heat-controlled. Shifting the operating times of the heat pump when solar radiation is at its highest could probably improve the performance of the systems even further. This will be a focus in the further course of the project.

Finally, I would like to thank the german federal ministry of economy and climate protection, the ptj, the Project Management Juelich and the industry and research partners whose work and financial support made this project possible.